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Abstract. From 23:10 to 23:50 UT on 18 March 2004, the Double Star TC-1 spacecraft detected eight flux ropes at the outbound crossing of the southern dawnside magnetopause. A notable guide field existed inside all ropes. In the mean time the Cluster spacecraft were staying in the magnetosheath and found that the events occurred under the condition of southward IMF B_z and dominant negative IMF B_y. There are six ropes that appeared quasi-periodically, with a repeated period being approximately 1–4 min. The last flux rope lasts for a longer time interval with a larger peak in the B_N variations; it can thus be referred to as a typical FTE. The 18 March 2004 event is quite similar to the multiple flux rope event observed by Cluster on 26 January 2001 at the northern duskside high-latitude magnetopause. A detailed comparison of these two events is made in the paper. Preliminary studies imply that both of these multiple flux ropes events seem to be produced by component reconnection at the dayside low-latitude magnetopause.

Keywords. Space plasma physics (Magnetic reconnection) – Magnetospheric physics (Magnetopause, cusp, and boundary layers; Solar wind-magnetosphere interactions)

1 Introduction

Magnetic reconnection at the magnetopause (MP) is the main process for the solar wind plasma to access the magnetosphere and for the magnetospheric particles to escape to the interplanetary space (e.g. Russell and Elphic, 1978; Cowley et al., 1982; Gosling et al., 1990).

While single-spacecraft measurements have provided ample in-situ evidence for the occurrence of reconnection at the MP (e.g. Sonnerup et al., 1981; Gosling et al., 1991; Onsager et al., 2001; Mozer et al., 2002), some fundamental questions about the large-scale spatial and temporal nature of reconnection remain unclear. For example, it is not yet known where reconnection first occurs when a noticeable interplanetary magnetic field (IMF) B_y is present. It is not known either whether reconnection at the MP is intrinsically intermittent or continuous. The relative importance of anti-parallel reconnection vs. component reconnection is still an unsolved outstanding question. Frequent observations at the MP of flux transfer events (FTEs) have been interpreted as signatures of intermittent reconnection. Measurements of flux ropes also provide some clues to evaluate the validity of component or anti-parallel reconnection models at the MP (Sonnerup et al., 1995; Phan et al., 2004; Pu et al., 2005a,b).

The apogee of the Double Star TC-1 satellite and the Cluster II are both in the solar wind during spring and late winter (Liu et al., 2005). This provides excellent opportunities to investigate reconnection at the dayside MP. From 23:10 to 23:50 UT on 18 March 2004, the TC-1 spacecraft detected eight flux ropes at the outbound crossing of the southern dawnside magnetopause. A notable guide field existed inside all ropes. The first six flux ropes occurred quasi-periodically with a repeated period being approximately 1–4 min. This event is quite similar to the multiple flux rope event observed by Cluster on 26 January 2001 at the northern

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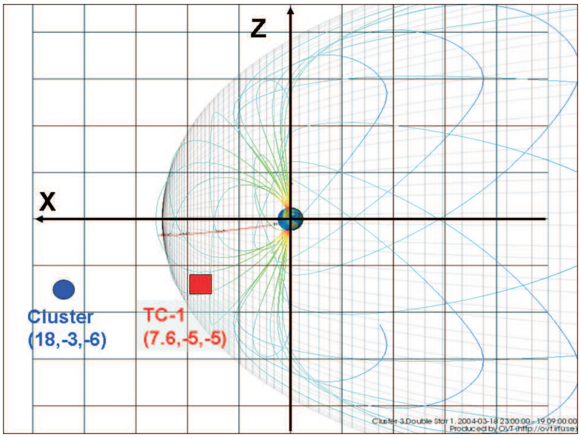

Fig. 1. The locations of TC-1 and Cluster spacecraft from 23:10 to 23:50 UT on 18 March 2004. The shape of the magnetosphere is produced by OVT (http://ovt.irfu.se).

duskside high-latitude magnetopause (Bosqued et al., 2001; Huang et al., 2004; Phan et al., 2004; Pu et al., 2005a). A preliminary comparison of these two events is made in the paper.

2 Observations

In this study, we use 4-s resolution data from Fluxgate Magnetometer (FGM) (Balogh et al., 1997; Carr et al., 2005) and Hot Ion Analyzer (HIA) (Rème et al., 1997) on board TC-1 and Cluster. The Double Star TC-1 orbit has an apogee of ~13.4 R_E (R_E, the radius of the Earth), a perigee of 577 km, an inclination of 28.25°, and a period of 27.4 h. Further details of the TC-1 instrumentation and orbits are given by Liu et al. (2005) and references therein.

Figure 1 shows the location of the TC-1 and Cluster spacecraft during the outbound crossing of the southern dawnside MP from 23:10 to 23:50 UT on 18 March 2004. TC-1 GSM position was (7.5, –5.5, –5.4) R_E. In the mean time the Cluster spacecraft were staying in the magnetosheath at (18.0, –3.1, –6.2) R_E (GSM), which worked as a good monitor of the IMF and solar wind plasma states.

Figure 2 shows the TC-1 outbound crossing of the southern dawnside MP. The southward IMF B_z and noticeably negative IMF B_y measurements by Cluster spacecraft are shown in the bottom of the figure; colors are as in the other panels: black for the x-component, green for the y-component and red for the z-component. The velocity, density and temperature of the solar wind plasma are listed on the right of this panel. The magnetic field and plasma velocity observed by TC-1 are showed in both GSM coordinates (Figs. 2e, f) and magnetopause boundary normal coordinates (LMN) (Figs. 2c, d). The masks in Fig. 2 show the intervals of eight flux ropes events with a clear reverse (-/+) bipolar B_N signature. This is consistent with the fact that the TC-1 position was southward of the equator. Notable guide field (B_M component) existed inside all ropes. The spectrum of ion fluxes (Fig. 2a) show clearly that flux ropes 1–6 are magnetospheric boundary layer events and ropes 7 and 8 are located in the magnetosheath boundary layer. In literature the occurrence of flux rope is often referred to as FTE of which the time interval lasts for about 2 min, on average, whereas the first six flux ropes appear only for less than 1 min, with apparently smaller peaks in the B_N variations. For this reason we refer the last flux rope as an FTE to distinguish it from the other seven, though the terms flux ropes and FTEs have often been used interchangeably.

Table 1 shows the axis orientations of all flux ropes in the GSM coordinates obtained by the minimum variance analysis (MVA) of the magnetic field. By and large, the flux ropes are along the dawn-dusk direction, because the y-component is dominant in all orientation vectors (Φ and Θ are the corresponding azimuthal angle and polar angle, respectively). The deHoffmann-Teller (HT) velocities of these ropes are also listed in Table 1. A well-defined HT frame exists in each event, since all residual electric fields are very small ($E(HT)/E(0)<8\%$). This means that all these flux ropes, to a certain extent, were time-stationary during TC-1 crossings. Note that the HT velocity $\mathbf{V_{HT}}$ of all events is southward. This indicates that the magnetic reconnection locations where the flux ropes were generated are to the north of the satellite. We will discuss this point later.

3 Discussion and conclusions

From 23:10 to 23:50 UT on 18 March 2004, the TC-1 spacecraft detected seven flux ropes and one FTE during the outbound crossing of the southern dawnside magnetopause. Six of the flux ropes appeared quasi-periodically, with a repeated period being approximately 1–4 min. The FTE appeared a few minutes later. This multiple flux rope event is quite similar to the event observed by Cluster on 26 January 2001 at the northern duskside high-latitude magnetopause which has been analyzed in detail by Bosqued et al. (2001) and Phan et al. (2004). Eight flux ropes and one FTE in the magnetosheath boundary layer and magnetosheath have been detected by Cluster from 11:10–11:34 UT. The magnetic field and plasma observations by four Cluster satellites are all similar during that interval. Figure 3 shows the measurements of energetic proton flux by RAPID (Wilken et al., 1997), magnetic field by FGM and plasma velocity by CIS on board C3 in the MP boundary normal coordinates (LMN). One sees that eight flux ropes appeared quasi-periodically with a repeated period being approximately 72 s and an FTE appeared 8 min later. The detailed analysis of this multiple flux rope event has been done by Huang et al. (2004) and Pu et al. (2005a). It is of interest to note that in the 26 January 2001 event and the 18 March 2004 event, the repeated frequencies of flux ropes are both much shorter than the averaged occurrence period of the FTE (about 8–11 min), and that an FTE rope appeared later after the multiple flux ropes. An even more interesting feature is the fact that the $\mathbf{V_{HT}}$ of all

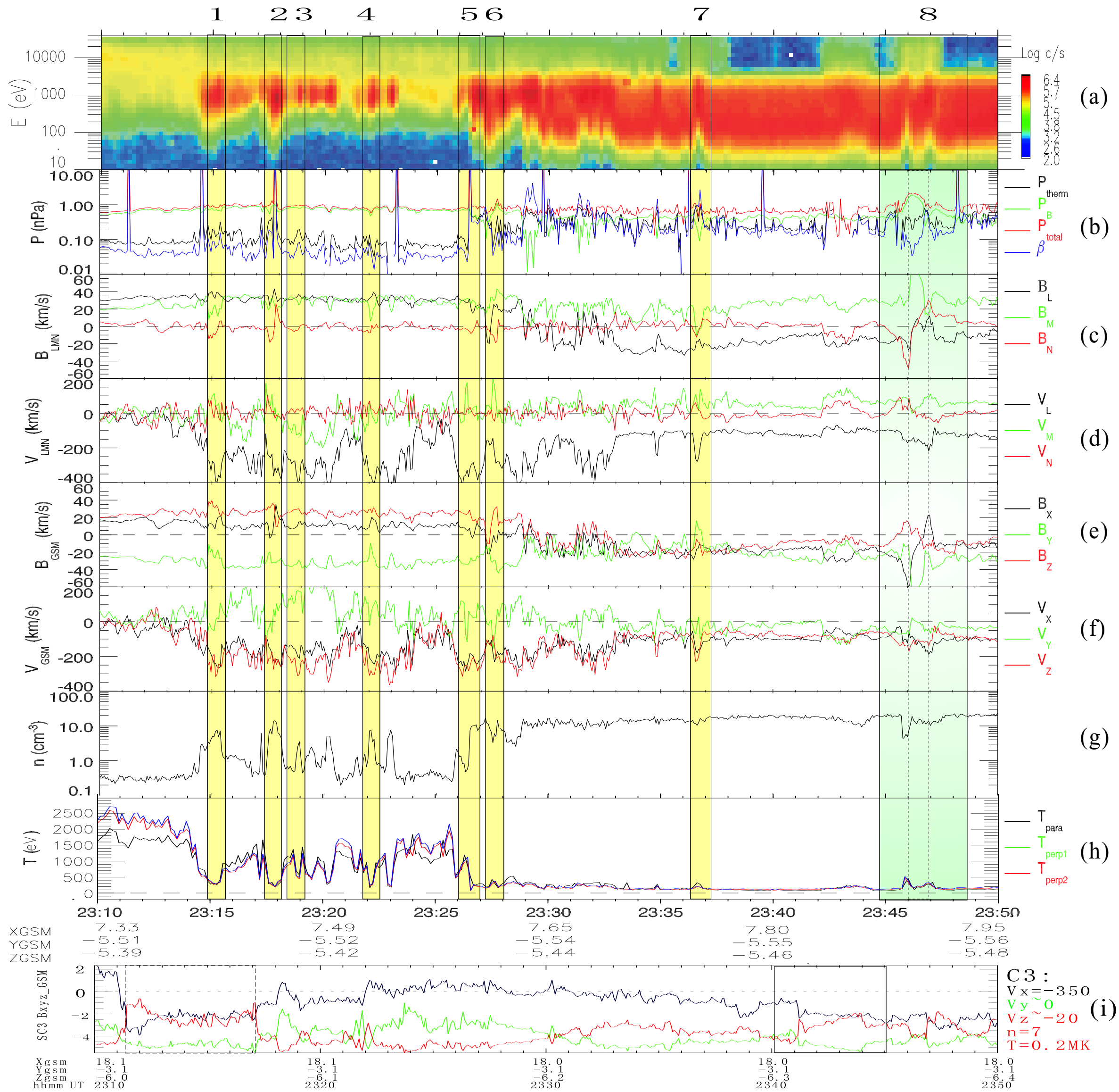

Fig. 2. Overview of the TC-1 and Cluster measurements on 18 March 2004. The bottom panel shows magnetic field measurements from Cluster and the rest of the panels are from TC-1: **(a)** spectrum of ion flux, **(b)** plasma pressure and magnetic pressure, **(c)–(d)** magnetic field and plasma velocity in the LMN coordinates, **(e–(h)** magnetic field, plasma velocity, density and temperature in the GSM coordinate system. The yellow masks show the flux ropes and the blue mask shows the FTE.

flux ropes in 18 March 2004 event is southward, while in the 26 January 2001 event it is northward. This might provide some clues for study on the reconnection processes that generated the flux ropes and FTE in the two cases. The IMF and solar wind plasma parameters of these two events are listed in Table. 2. It is seen that the IMF and solar wind conditions of the two events are quite similar; in particular, the IMF B_z is southward, accompanied by a noticeable dawnward B_y. No apparent difference in the solar wind conditions is found during the intervals of multiple flux ropes and FTE in both events. We have looked at the solar wind plasma beta, velocity, IMF direction and other observed parameters. No indications for the quasi-periodic appearance of flux ropes are seen. Perhaps more detailed studies on local conditions at the reconnection sites are needed.

The IMF and solar wind conditions in the 18 March 2004 and the 26 January 2004 cases are quite close. Therefore, these two events should have a similar reconnection scenario and global signatures. Flux ropes in these events are both moving poleward; the projections of $\mathbf{V_{HT}}$ onto the GSM (y, z) plane are more or less opposite to each other. These imply that the X-lines, where the flux ropes were produced, are located in between the TC-1 and Cluster positions on the low-latitude MP, with almost the same tilted angles with respect

Table 1. The axis orientation and V_{HT} of the flux ropes in the GSM coordinates.

Event	Interval (UT)	Axis orientation (Φ, Θ)	V_{HT} (km/s)	E(HT)/E(0)
1	23:14:31-23:15:24	(0.163, 0.795, 0.585) (78.4, 54.2)	(–116, –116, –26)	0.073
2	23:17:16–23:18:09	(–0.430, 0.883, –0.192) (115.9, 79.0)	(–171, –3, –211)	0.027
3	23:18:23–23:19:08	(–0.311, 0.627, –0.714) (116.4, –44.4)	(–140, 74, –186)	0.037
4	23:22:52–23:23:25	(0.473, 0.851, 0.230) (60.9, 76.8)	(–142, –90, –134)	0.026
5	23:26:12–23:27:09	(0.237, 0.774, –0.587) (73.0, –54.1)	(–234, 96, –233)	0.057
6	23:27:13–23:28:10	(0.626, 0.762, 0.166) (50.6, 80.4)	(–188, –30, –139)	0.025
7	23:36:03–23:36:47	(0.289, 0.891, 0.355) (72.3, 69.2)	(–200, –59, –166)	0.067
8	23:44:32–23:48:28	(0.159, 0.930, –0.332) (80.3, –70.6)	(–139, –92, –117)	0.032

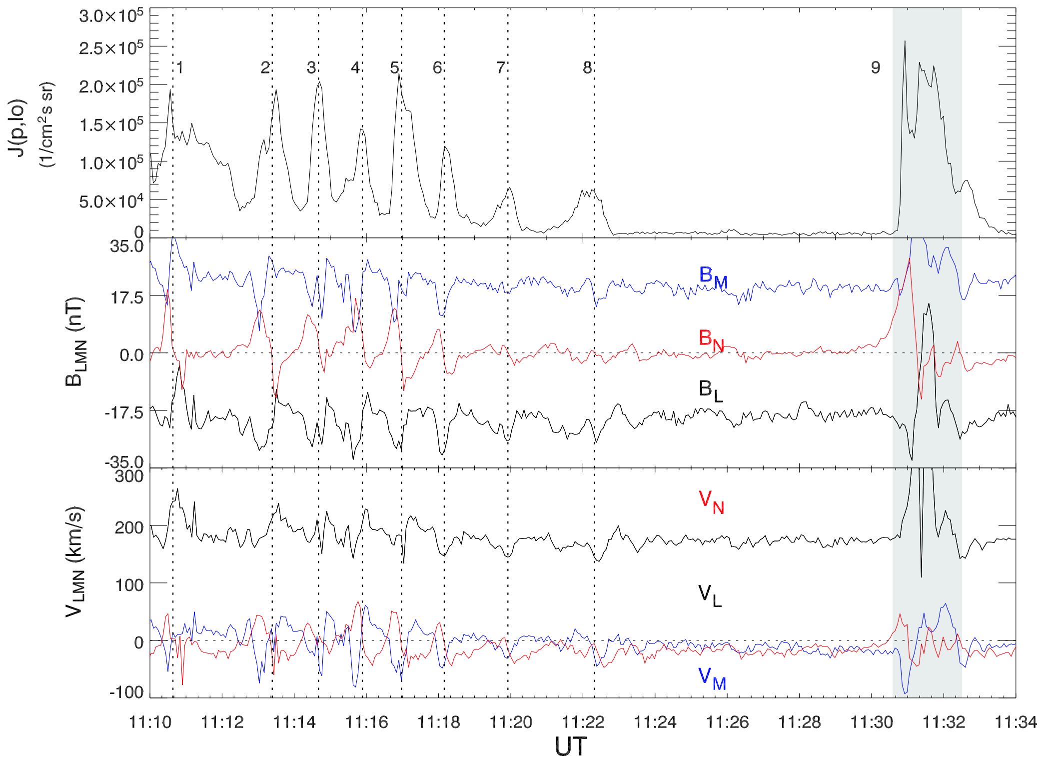

Fig. 3. The multiple flux rope event observed by Cluster (C3) on 26 January 2001. The panels, from top to bottom are: the flux of energetic protons, the magnetic field and the velocity of plasma in the MP boundary normal coordinates (LMN). The eight vertical dash lines mark the flux ropes and the light green shadow masks the FTE.

Table 2. Average values of the IMF and solar wind plasma parameters for 18 March and 26 January events. The arrow means that the parameter changes with time.

Parameter	18 March 2004	26 January 2001
Bx (nT)	–0.5 → –1	–1 → –2
By (nT)	–6	–5 → –4
Bz (nT)	–3	–2 → –4
Vx (km/s)	–350	–350
n (cm^{-3})	4.5	7.0

to the equatorial plane. This is consistent with the component merging model with negative IMF B_z and B_y (Cowley et al., 1976; Sonnerup et al., 1981; Gosling et al., 1990). The component reconnection model suggests that when a nonzero IMF B_y is present, MP reconnection for southward B_z takes place preferentially in the subsolar region along an X-line passing through the subsolar point with a tilt, depending on the orientation of the IMF. Based on these arguments and our MVA and HT analysis, we draw a suggestive diagram in the GSM (y-z) plane in Fig. 4 to show the global view of a pair of flux ropes in events 18 March 2004 and 26 January 2001.

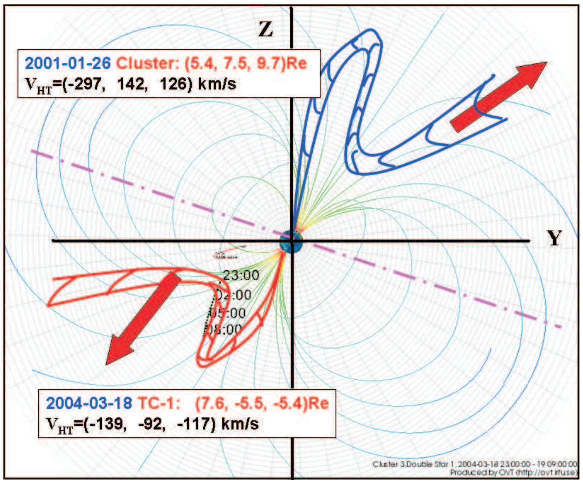

Fig. 4. Schematic drawing of a global view of flux rope in the Y-Z plane of GSM coordinates. The red arrows show the moving directions of flux ropes, and the pink dash line shows the suggested location of reconnection X-line.

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